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Lepton Number Conservation, Long-lived Quarks and Superweak Bileptonic Decays

Paul Howard Frampton*
Oxford, UK.

Abstract

In the upcoming LHC Run 2, at $\sqrt{s} \sim 13$ TeV, it is suggested to seek unusually charged ($Q = -4/3$ and $+5/3$) quarks with mass $M_Q \sim 3$ TeV which carry lepton number ($L = +2$ and -2 respectively) and decay superweakly to a bilepton Y with mass $M_Y \sim 2.5$ TeV and a usual quark. These long-lived decays will have displaced decay vertices and produce a striking final state in pp which contains two separated jets together with two pairs of correlated like-sign charged leptons. Such a process was inaccessible energetically in LHC Run 1 with $\sqrt{s} \sim 8$ TeV. The simplest theoretical explanation is the 331-model which has new physics necessarily below 4 TeV and which explains the existence of three families by anomaly cancellation.

*e-mail address: paul.h.frampton@gmail.com

1 Introduction

In addition to the theoretical predictions for the LHC of supersymmetry and dark matter, the discovery of either of which would be revolutionary, it is worth being more conservative and to consider instead the ancient art of model-building in gauge theories which extend the standard model and are motivated and testable. In particular, we here suggest that LHC experimentalists seek unusually-charged quarks ($Q = -4/3, +5/3$) which are produced strongly and decay slowly by weaker than weak interactions, are constrained to lie below 4 TeV, and motivated by an explanation of three families.

The 331 model [1, 2] has provoked sufficient interest that there exist a number of studies of its phenomenological ramifications. One aspect which has, however, escaped much attention is the issue of lepton number (L) conservation and the role it plays in suppressing the decay rate for the heavy quarks. Although there are reviews of 331 bilepton physics [3, 4], the slow decays of the 331 heavy quarks have not been previously emphasized. The upgraded LHC seems tailor-made for discovery of these heavy quarks and its Run 2 could expose them.

The familiar quarks (u, d, c, s, t, b) have baryon number $B = 1/3$ and $L = 0$. The familiar leptons ($e-, \mu-, \tau-, \nu_e, \nu_\mu, \nu_\tau$) have $B = 0$ and $L = 1$. The exotically-charged quarks of the 331 model carry nonzero L as follows: D and S have $B = 1/3$ and $L = 2$; T has $B = 1/3$ and $L = -2$.

An important final-state particle at the LHC is the penetrating and unstable muon which decays via the weak interaction

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (1)$$

with a long lifetime $\tau_\mu \sim 2 \times 10^{-6}$ s according [5, 6] to the tree-level formula

$$\tau_\mu = \frac{g_2^4 M_\mu^5}{12288\pi M_W^4} \quad (2)$$

where g_2 is the electroweak $SU(2)$ gauge coupling with $g_2^2 = 8M_W^2 G_F$. Other than the muon, the only long-lived charged particles in the standard model are the stable electron and proton. But there may be about to appear an entirely new breed of metastable charged elementary particles to enter this small group.

It is well-known and investigated that if there exists a fourth family of quarks, then they can mix only very little with the first three families because the 3×3 CKM matrix [7, 8] is close to being unitary. Hence, the additional quarks of the fourth family would have interesting long lifetimes as discussed in [9, 10]. In the 331-model it is assumed that such sequential quarks do not exist and it is predicted that there are only three families.

Here we are interested in quarks which are long-lived for a different reason, namely L conservation. The consequent superweak interaction is mediated by Y bilepton intermediate vector bosons in the 331-model and a possible particle discovery at LHC is of a sibling to the W^\pm . For instance Y^- mediates the abnormal muon decay

$$\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu \quad (3)$$

which is suppressed relative to the normal decay, Eqs. (1,2) by a factor

$$f = (M_W/M_Y)^4. \quad (4)$$

and, given $M_W \simeq 80$ GeV, the question is whether the value of M_Y can be arbitrarily large. In the present context the answer is no.

In the 331-model there is an important theoretical upper limit $M_Y \leq 4\text{TeV}$ for the symmetry breaking to the standard model, arising from the renormalization group behavior of the electroweak mixing angle and the group embedding. The value $\sin^2 \theta(M_Z) = 0.231$ runs upward with energy scale and reaches $\sin^2 \theta(E) = 0.250$, a singular point of the embedding $SU(2)_L \subset SU(3)_L$, at $E = 4$ TeV. This was first analysed in [1] and has been much more recently confirmed in [11]. This intrinsic 331 upper limit is what underlies the claim that the new physics is at a mass scale especially befitting LHC's Run 2.

Theoretically then $M_Y \lesssim 4$ TeV while experimentally $M_Y \geq 1.5$ TeV. We may reasonably take $M_Y = 2.5$ TeV ($\simeq 10\sqrt{10}M_W$) as an illustration whereupon the suppression factor f in Eq. (4) is $f \simeq 10^{-6}$. The experimental upper limit for process Eq.(3) is [12] disappointing, the branching ratio being restricted merely to $\leq 1.2\%$. The 331 prediction is that this branching ratio is four orders of magnitude smaller, $\sim 10^{-6}$.

By superweak interaction we therefore mean the weak interaction further suppressed for bilepton mediation by the factor f in Eq.(4) relative to the W exchange. Superweakness implies that the exotic quarks (D, S, T) are long-lived.

2 Long-Lived Quarks

In the 331-model which requires exactly three families there are three additional exotic quarks(D, S, T), one in each family. The gauge group is $SU(3)_C \times SU(3)_L \times U(1)$ and for the first family the quarks are in the triplet and three singlets of $SU(3)_L$

$$\begin{pmatrix} u^\alpha \\ d^\alpha \\ D^\alpha \end{pmatrix}_L \quad \bar{D}_{L,\alpha}, \quad \bar{d}_{L,\alpha}, \quad \bar{u}_{L,\alpha}, \quad (5)$$

and similarly for the second family

$$\begin{pmatrix} c^\alpha \\ s^\alpha \\ S^\alpha \end{pmatrix}_L \quad \bar{S}_{L,\alpha}, \quad \bar{s}_{L,\alpha}, \quad \bar{c}_{L,\alpha}. \quad (6)$$

The quarks of the third family are assigned differently, in one antitriplet and three singlets

$$\begin{pmatrix} T^\alpha \\ t^\alpha \\ b^\alpha \end{pmatrix}_L \quad \bar{b}_{L,\alpha}, \quad \bar{t}_{L,\alpha}, \quad \bar{T}_{L,\alpha}. \quad (7)$$

The established weak gauge bosons (W^-, W^0, W^+) with $W^0 \equiv Z \cos \theta + \gamma \sin \theta$ are augmented by five more, a Z' and four bileptons (Y^+, Y^{++}) ($L = -2$) and (Y^-, Y^{--}) ($L = +2$).

The superweak decays of D are (we exhibit only the muonic decays, the most readily detected)

$$D \rightarrow u + Y^{--} \rightarrow u + \mu^- + \mu^- \quad (8)$$

has a displaced vertex in the silicon detector. There is the alternative equally long-lived decay

$$D \rightarrow d + Y^- \rightarrow d + \mu^- + \nu_\mu, \quad (9)$$

but the neutrino ν_μ makes process Eq. (9) far more challenging to detect than Eq.(8).

The sequential second family exotic quark S has similar long-lived decays

$$\begin{aligned} S &\rightarrow c + Y^{--} \rightarrow c + \mu^- + \mu^- \\ S &\rightarrow s + Y^- \rightarrow s + \mu^- + \nu_\mu \end{aligned} \quad (10)$$

In the 331 model the third family, on the other hand, the T has $Q = +4/3$ and lepton number $L = -2$ so that its long-lived decays have flipped electric charges

$$\begin{aligned} T &\rightarrow b + Y^{++} \rightarrow b + \mu^+ + \mu^+ \\ T &\rightarrow t + Y^+ \rightarrow t + \mu^+ + \bar{\nu}_\mu \end{aligned} \quad (11)$$

The antiquarks ($\bar{D}, \bar{S}, \bar{T}$) have superweak decays into the corresponding charge conjugate final states

$$\begin{aligned}
\bar{D} &\rightarrow \bar{u} + Y^{++} \rightarrow \bar{u} + \mu^+ + \mu^+ \\
\bar{D} &\rightarrow \bar{d} + Y^+ \rightarrow \bar{d} + \mu^+ + \nu_\mu \\
\bar{S} &\rightarrow \bar{c} + Y^{++} \rightarrow \bar{c} + \mu^+ + \mu^+ \\
\bar{S} &\rightarrow \bar{s} + Y^+ \rightarrow \bar{s} + \mu^+ + \nu_\mu \\
\bar{T} &\rightarrow \bar{b} + Y^{--} \rightarrow \bar{b} + \mu^- + \mu^- \\
\bar{T} &\rightarrow \bar{t} + Y^- \rightarrow \bar{t} + \mu^- + \bar{\nu}_\mu
\end{aligned} \tag{12}$$

We take $M_Y = 2.5$ TeV and can assume a normal quark mass hierarchy is $M_T > M_S > M_D$ with $M_D \sim 3$ TeV. The lowest threshold will then be for $\bar{D}D$ pair production by strong interactions so the most interesting event would be $pp \rightarrow \bar{D}D + \text{any}$.

By strong interactions, two gluons can produce the $\bar{D}D$ pair, practicable only at Run 2 of the LHC with 13 TeV. The \bar{D}, D quarks being long-lived will travel a macroscopic distance from the production vertex.

The \bar{D}, D quarks decay to bileptons and the most striking signature would surely be an event with

$$\bar{D} \rightarrow \bar{u} + Y^{++} \rightarrow \bar{u} + \mu^+ + \mu^+ \tag{13}$$

and the counterpart

$$D \rightarrow u + Y^{--} \rightarrow u + \mu^- + \mu^- \tag{14}$$

In Eqs.(13,14), the light quarks \bar{u}, u will hadronize to high-energy jets which the LHC physicists are well equipped to reconstruct. The two jets will originate from the separate displaced decay vertices for \bar{D} and D . The like-sign pairs of muons will centre around an invariant bilepton mass $M_Y \sim 2.5$ TeV, which can be determined.

This bilepton mass can subsequently be confirmed by the other channels $\mu^- \nu_\mu, e^- e^-, e^- \nu_e, \tau^- \tau^-, \text{etc.}$

3 Discussion

The two most heralded targets for the LHC, beyond the Higgs boson, were to confirm weak-scale supersymmetry and to produce dark matter. If weak-scale supersymmetry existed, it was expected to appear in the 2009-2013 Run 1 at ~ 8 TeV, but did not. The excluded parameters narrow the likelihood of its discovery in Run 2. Once weak-scale supersymmetry is abandoned, the link between the weak scale and dark matter mass is lost. The masses for suggested DM candidates range from axions with mass $\sim 10^{-15}$ GeV to black holes with mass $\sim 10^{62}$ GeV so it would now require remarkably good fortune for it to show up at the LHC. The possibility of extra spatial dimensions large enough to be detected at the LHC is not strongly motivated.

There are not many theoretical models with a strong reason to expect the relevant new physics scale to be specifically in the LHC Run 2 (13 TeV) regime, as opposed to the Run 1 (8 TeV) one. Among these, the 331 model does naturally contain an multi-TeV scale [1, 11] in its analysis. Its long-lived charged quarks are predicted in the appropriate mass range hence more likely to be produced in Run 2 than Run 1. The signature of such an event is striking and although this would not immediately explain all the parameters of the standard model it will give a second stronger explanation of why there exist three families beyond the ingenious observation in [8] that it accommodates the observed CP violation in flavor-changing weak interactions.

If such a discovery is made, what is the next step in the theory? It would suggest even further cousins of the W and Y gauge bosons which could appear in additional $SU(3)$ factors. Nonabelian subsumption of the $U(1)_Y$ gauge group factor is hinted at by avoidance of the Landau pole. At present this remains idle speculation until an electroweak $SU(3)$ has empirical evidence which would, nevertheless, firmly justify the construction of higher energy apparatus to answer further questions.

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